

Modelling of Injection into Geothermal Systems

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MODELLING OF INJECTION INTO GEOTHERMAL SYSTEMS

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SUMMARY – In this study, modified versions of the hypothetical geothermal systems constructed by Sigurdsson et al., 1995, are used to examine the effects of injection on production for various scenarios. The main differences between the models presented here and the original Sigurdsson models are the recharge conditions. In some of our models we allow for lateral recharge by adding extra blocks on the sides of the model and we allow for deep recharge by adding extra blocks at the base of the model. The results obtained from the simulations show that the effects of injection depend on the recharge conditions and reservoir parameters.

1. INTRODUCTION

The aim of the present study is to use computer modelling to investigate the effect on steam production of injection in a geothermal reservoir, and in particular the longevity of the resource with regard to steam production. One of the few previous modelling studies on the topic was carried out by Sigurdsson et al., 1995, on an idealised reservoir. For the present study the Sigurdsson model was chosen as a reference case but his model has been extended to investigate the effect of the natural recharge from shallow groundwater, from the basement of the system and laterally from the boundaries of the system. Various cases are considered for the different injection strategies and for different reservoir permeability. The geothermal simulator TOUGH2 (Pruess et al., 1999) has been used for all the simulations described in this paper.

2. BACKGROUND ON INJECTION

The effect of injection on production depends on the structure of the individual system but there are some generic differences depending on whether the geothermal system is vapour-dominated, liquid-dominated or hot water.

Vapour-dominated. During production, as the pressure decreases, more and more of the immobile water boils to form steam which then flows towards the production wells. By their very nature, vapour-dominated two-phase systems have low permeability in the reservoir zone and very low permeability surrounding the reservoir. If this were not the case, cold water would flow into the low-pressure vapour-dominated reservoir from the surrounding cool rock. Thus the water in a vapour-dominated reservoir is not replenished by natural recharge and, after some years of production, parts of the reservoir may run out of immobile water and become superheated (i.e. the temperature of the steam is above the boiling point). In this case it may be beneficial to inject water directly above the depleted reservoir and

close to the production wells. In some cases, extra water as well as the steam condensate has been injected. This strategy has been successfully followed at, for example, The Geysers in California (Goyal, 1998) and Larderello in Italy (Cappetti and Ceppatelli, 2005).

High-Enthalpy, Liquid-Dominated. In their pre-exploitation or natural state these systems contain all, or mostly, very hot water (i.e. the boiling zones are non-existent or small). However, when production wells are drilled, at least some of them discharge at quite high enthalpies (in the range 1500 – 2000 kJ/kg). This is because boiling occurs at the feed zones of the wells, caused by large pressure drops. This situation is in turn caused by low reservoir permeability, often resulting from a few large fractures within a “tight” rock matrix. The permeability in the rock surrounding the hot reservoir in such systems may be similar to that inside the reservoir, i.e. there is not necessarily any permeability contrast between the inside (the hot part) and outside (the cold part) of the reservoir.

The distinguishing feature between this type of system and the low-enthalpy liquid-dominated systems discussed in the next section is the level of fracturing. The high enthalpy version (e.g. Mokai) typically has a few major fractures whereas the low enthalpy versions (e.g. Wairakei) have more general fracturing and more widely spread permeability.

In high enthalpy liquid-dominated systems, the boiling zones that develop as a result of production are typically localised and have a high steam fraction. The steam fraction may increase during production, and in some cases a localised vapour-dominated zone may develop. In low enthalpy liquid-dominated systems, by comparison, the boiling zones are large in extent and are “wet”, i.e. they have a low steam fraction. The large pressure drop at production wells and the boiling induced in the reservoir are not undesirable effects from a reservoir engineering

point of view. A high enthalpy mixture of water and steam is an advantage because the conversion of thermal energy to electricity is more efficient and less separated water has to be dealt with. The large drop in reservoir pressure may result in some subsidence (Bodvarsson and Stefansson, 1989), a reduction in surface flows in liquid features and an increased heat flow, mainly from steam, through the surface at some locations.

The pressure drop at the production wells is in practice buffered by the boiling process. The pressure declines rapidly until boiling occurs, and then the pressure declines more slowly, following a temperature decline resulting from two processes:

- The heat extracted from the rock matrix boils off the water, turning it into steam.
- The cool recharge (mainly water rather than steam) is attracted to the low-pressure zone both from the top and the sides of the reservoir.

In some cases, hot deep recharge offsets the cool recharge or even exceeds the cool recharge, depending on the balance between lateral and vertical permeabilities.

In high-enthalpy, liquid-dominated systems injecting cold water into the production zone will cause faster cooling of the production wells. In some cases, it may even suppress boiling and cause the production enthalpy to drop to that of hot water. This type of system does not run out of water, as is sometimes the case for vapour-dominated systems. Also, these systems do not suffer from excessive pressure decline and do not require pressure maintenance, as can be the case for hot water systems. Therefore, from a reservoir engineering perspective there is no reason to inject infield in high-enthalpy, liquid-dominated, two-phase geothermal systems. Experience at a number of fields supports this statement. Often injection in high-enthalpy, liquid-dominated, two-phase geothermal systems has resulted in adverse thermal breakthrough and a consequent move of injection outfield, e.g. Cerro Prieto (Lippmann et al., 2004), Tiwi (Sugiaman et al., 2004).

Low-Enthalpy, Liquid-Dominated. These systems are quite similar to the high-enthalpy systems, except for their permeability. They are typically much more generally fractured with larger permeability. Thus when production begins, the pressure does not drop as much and less boiling occurs. Hence production enthalpies are lower - typically not very much above those for hot water. Again, there is no general permeability boundary at the edge of the hot reservoir, and cold recharge from the sides of the reservoir can easily flow into it. Typically, vertical permeabilities are also high. As a result, cold recharge may flow down into the reservoir from above or extra hot recharge may flow into the reservoir from below. The balance between hot and cold recharge varies from one

system to the next. The main experience of infield injection in this type of geothermal field is that it has caused degradation of the resource by thermal breakthrough and injection has been moved outfield, e.g. Miravalles (Gonzalez-Vargas et al., 2005), Kakkonda (Stefansson, 1997).

Hotwater. In these systems no boiling occurs before or after production commences. Thus large pressure gradients must be set up to cause production fluid to flow towards the wells. Without any injection, however, the pressure will continue to decline until the induced recharge from above, below and laterally matches the overall production rate. In many cases, without injection, the pressure will drop too low to allow the production wells to continue operation. Injection assists by providing an extra mass flow and by boosting pressures. From this perspective, it is desirable to have infield injection with injection wells close to production wells in such systems. However, there is a fundamental tension between this beneficial pressure maintenance effect and thermal breakthrough (when the cool injected water reaches the production wells). In some fields, particularly those with a few large faults, thermal breakthrough has occurred rapidly and injection has been moved further out, e.g. Brady, USA (Krieger and Sponsler, 2002).

Thus the design of an injection strategy for a geothermal system is a complex problem and several parameters need to be considered (Stefansson, 1997), for example: disposal of waste fluid, cost, reservoir temperature - thermal breakthrough, reservoir pressure - production decline, temperature of injected fluid, silica scaling, chemistry changes in reservoir fluid, subsidence and the selection of injection locations.

3. STATEMENT OF THE PROBLEM

The first aim of this study was to reproduce the result obtained by Sigurdsson et al., 1995. The Sigurdsson model consists of four layers. The top two layers are 300m thick and correspond to the ground water system and a cap-rock layer respectively. The other two layers are each 400m thick and represent the reservoir rock.

The areal extent of the layers is 1.6km x 2.0km. A subgrid consisting of two radial elements was used around the production wells. The detailed grid structure of the model is defined in Sigurdsson et al., 1995 and Sigurdsson and Stefansson, 1998. Table 1 shows thermal and mechanical properties used in the numerical model. Figure 1 shows the areal grid structure of the model used in the present study and geometric locations of production and injection wells. The grid structure used is finer and more regular than that used by Sigurdsson et al. The vertical layer

structure of the present model is the same as Sigurdsson's model.

Table 1. Thermal and mechanical parameters

Rock Parameters		
Matrix density, kg/m ³		2650
Specific heat, J/(kg°C)		1000
Thermal conductivity, W/(m°C)		1.7
Case A	Porosity, %	Permeability, m ²
Ground layer	10	6.0x10 ⁻¹⁵
Caprock	5	0.25x10 ⁻¹⁵
Upper reservoir layer	5	3.5x10 ⁻¹⁵
Lower reservoir layer	5	3.5x10 ⁻¹⁵
Case B	Porosity, %	Permeability, m ²
Ground layer	10	6.0x10 ⁻¹⁵
Caprock	5	0.25x10 ⁻¹⁵
Upper reservoir layer	5	17.5x10 ⁻¹⁵
Lower reservoir layer	5	17.5x10 ⁻¹⁵
Relative Permeability Linear Curves		
S _{lr}		0.30
S _{vr}		0.05
S _{pv}		0.70
Well Parameters		
Productivity index, m ³		1.6x10 ⁻¹²
Pressure at upper layer, bar-a		30.0
Reinjection enthalpy, kJ/kg		721.0
Separator Conditions		
Pressure, bar-a		8.0
Temperature, °C		170.4

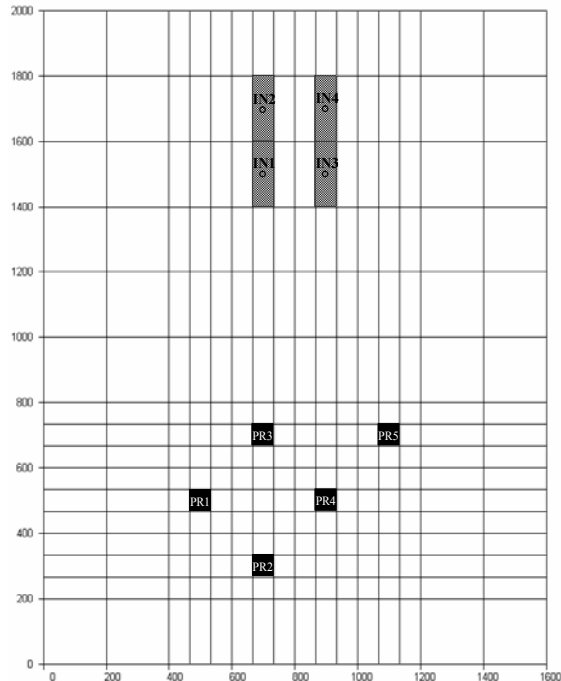


Figure 1. Grid structure showing location of production (black) and injection (grey) wells.

As can be seen from Figure 1, a dipole configuration was used for the location of the wells, with injection in the north of the reservoir and the production in the south. Sigurdsson et al., 1995 considered additional injection and production arrangements.

An exploitation period of 60 years was chosen. The separator pressure was set at 8 bar-a and a deliverability model was used that allows declining flow rates with time as the reservoir is depleted. Five production wells are used, open in both reservoir layers. For the injection cases, the same injection rates were used for all injection wells, open only in the upper reservoir layer.

This study is based on six steps:

- 1- Reproducing the result of Sigurdsson's closed (no lateral recharge) dipole model.
- 2- Modifying the model with the addition of an atmospheric layer to determine the effect of groundwater recharge. The initial conditions used in this model were the same as those specified by Sigurdsson et al., 1995.
- 3- Creating a 1D column natural state model with heat and mass flows chosen to give the best fit of temperature and pressure profiles to those used for Sigurdsson's model. These natural state profiles were then used as initial conditions in all later simulations.
- 4- Adding the deeper layers to the system to determine the effect deep recharge.
- 5- Testing the effect of different permeability values for these deep layers.
- 6- Examining the effect of large recharge blocks representing open boundaries for the high and low permeability reservoirs.

4. RESULTS

4.1. Sigurdsson's Dipole Model

Using the Case B reservoir rock parameters the results shown in Figure 2 were obtained.

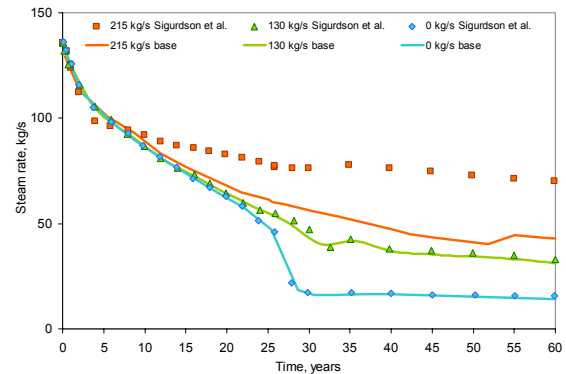


Figure 2. Steam production rates for Sigurdsson's model and the present study.

Good agreement with Sigurdsson's results was obtained for the no-injection case and the low-injection case (130kg/s). The differences are

easily explained in terms of the slightly different grid structure. However for the high-injection case (215kg/s) there is not good agreement. The reasons for this are not clear at present. It was possible to obtain good agreement with all other results shown by Sigurdsson et al., 1995, but it was only possible to approximately match the graph for the case of 215kg/s injection shown in Figure 2 if open rather than closed boundary conditions were used.

4.2. Addition of an Atmospheric Layer

Geothermal systems are mostly in hydraulic communication with the atmosphere and groundwater aquifers, and production and injection operations may be affected by this communication. To determine the effect of ground water recharge to the system, an atmospheric layer was added to Sigurdsson's model. Atmospheric conditions are maintained at the ground surface ($p = 1$ bar, $T = 5^\circ\text{C}$). Figure 3 shows the comparison of steam production rates for Sigurdsson's model and the model that has an atmospheric block. The system that allows groundwater recharge produces more steam than Sigurdsson's model. However it should be remembered that the basic model is closed on all sides and the top and bottom, so that the model reservoir tends to run out of mass and suffer large pressure declines. Therefore the addition of mass by injection or recharge from the surface improves the performance.

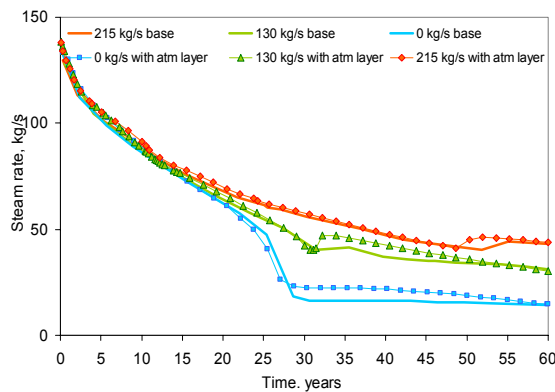


Figure 3. Steam production rates for Sigurdsson's closed model and a model with an open top.

The permeability of the cap-rock in the model is low ($0.25 \times 10^{-15} \text{ m}^2$). It would be interesting to carry out further numerical experiments varying this parameter.

4.3. One-dimensional vertical column model

One difficulty with Sigurdsson's model is that the initial conditions are not determined from a natural state model and thus they are not compatible with the model permeability structure and do not correspond to specified through-flows of heat and mass. As we wished to extend the model deeper and to experiment with the effect of

deep recharge it was decided to set up a 1-D vertical model to obtain natural state conditions as close as possible to Sigurdsson's initial conditions. This 1-D model has eight layers each $200\text{m} \times 200\text{m}$ in areal extent. The top four layers represent groundwater (300m), cap rock (300m), upper reservoir (400m) and lower reservoir (400m), respectively. The lower four layers, each 400m thick, represent the basement rock. They were added to the system to allow the investigation of deep recharge in the later stages of this study.

The rock parameters for Case B (see Table 1) were used and the basement rock permeability and the porosity were set at $0.025 \times 10^{-15} \text{ m}^2$ and 5 % respectively. A mass flow of 0.04kg/s at an enthalpy of 1540kJ/kg was input at the base of the model.

Figure 4 shows the comparison of temperature and pressure profiles which are obtained from the 1-D vertical column natural state model and the values defined by Sigurdsson et al., 1995 for two-phase conditions.

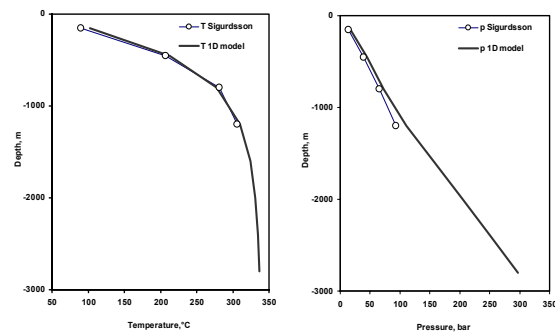


Figure 4. Temperature and pressure profiles from Sigurdsson et al., 1995 and the 1D column model.

In the reservoir layers these pressure and temperature values correspond to single phase water near the boiling point. Using the initial conditions from the 1D vertical model, instead of those given by Sigurdsson et al., 1995, does not significantly affect the steam production rates shown in Figure 3.

4.4. Deep recharge

To represent the natural upflow from the deeper part of the reservoir, four more layers were added beneath Sigurdsson's model. These four basement layers were each 400 m thick with rock parameters as for the 1D vertical column model. The natural state conditions from the 1D column model were used as the initial conditions for this system.

To investigate the sensitivity of the system behaviour to the reservoir permeability, two different permeability cases (Table 1) were tried. Case A is for low reservoir permeability (3.5×10^{-15}

15 m^2) and Case B is medium reservoir permeability ($17.5 \times 10^{-15} \text{ m}^2$).

Figure 5 shows the comparison of steam production rates for the three cases of injection and the model with and without basement layers. As can be seen from Figure 5, for the no-injection case even the very low permeability basement increases the steam flow from the model. Injection offsets this effect and for the medium- and high-injection cases the low permeability basement makes very little difference.

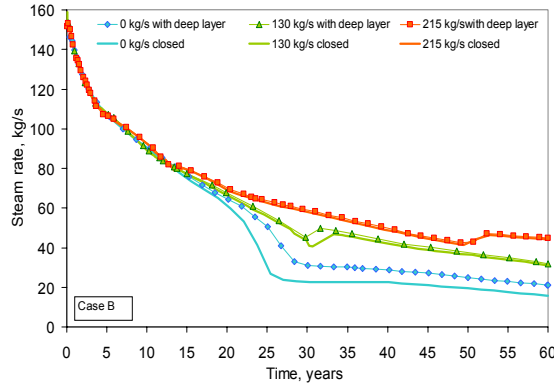


Figure 5. Steam production rates for Sigurdsson's closed model and a model with a very low permeability basement ($0.25 \times 10^{-16} \text{ m}^2$).

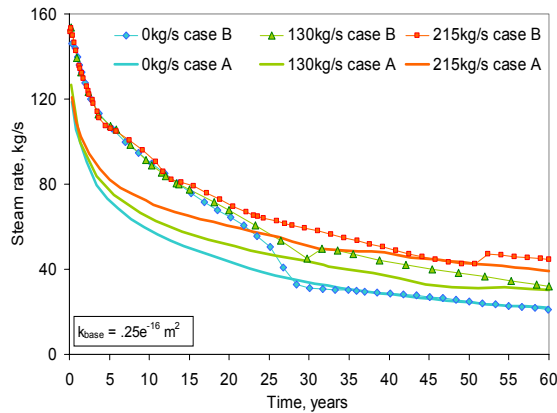


Figure 6. Steam production rates for a model with a very low permeability basement ($0.25 \times 10^{-16} \text{ m}^2$).

The effect of increasing the permeability of the basement rock is shown in Figure 6, 7 and 8. Results for low (Case A) and medium (Case B) reservoir permeability are shown. For a very low permeability of the basement the qualitative effect of injection is same as for Sigurdsson's model i.e. the long-term steam flow is enhanced by injection (see Fig. 6). For Case A the steam flow drops more quickly until about 30 years and then the results are similar to those for Case B. The results are similar when the basement permeability is increased to $0.25 \times 10^{-15} \text{ m}^2$ (see Fig. 7).

However, as shown in Figure 8, for Case B with a higher basement permeability ($1.0 \times 10^{-15} \text{ m}^2$) the behaviour changes qualitatively. The highest

injection rate no longer produces the highest steam flow, i.e. injection has an adverse effect on steam production. The results for Case A are somewhat different with the medium injection case producing the lowest long-term steam flow.

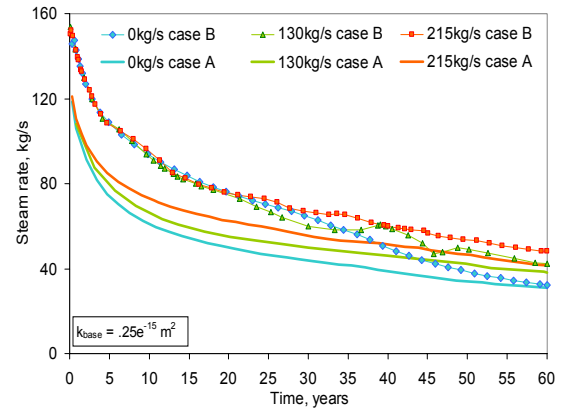


Figure 7. Steam production rates for a model with a low permeability basement ($0.25 \times 10^{-15} \text{ m}^2$).

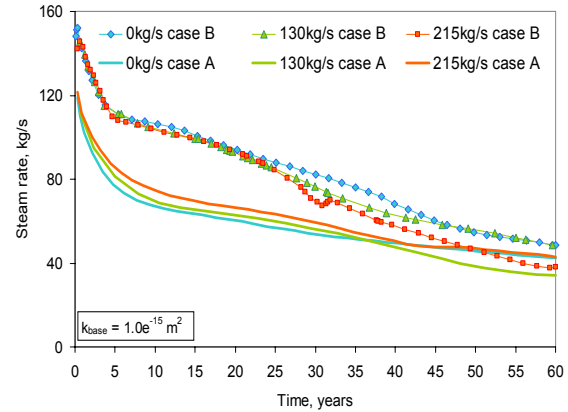


Figure 8. Steam production rates for a model with a medium permeability basement ($1 \times 10^{-15} \text{ m}^2$).

4.5 Lateral recharge

To explore the effect of lateral recharge, large boundary blocks were added at the sides of the model. To allow for lateral recharge three sizes of boundary blocks were investigated: 1.2km in length, 6km in length (both used by Sigurdsson et al., 1995) and a very large, effectively infinite length. Following Sigurdsson et al., 1995, the permeability of the large boundary blocks was set to be 43% of the value for the reservoir blocks. Both Case A and Case B were used to investigate low and medium permeability reservoirs, respectively, and the basement rock permeability was set at the low value of $0.025 \times 10^{-15} \text{ m}^2$. The initial conditions for the boundary blocks were chosen to be the same as for the reservoir blocks.

As can be seen by comparing Figure 9 and Figure 10 with Figure 6, a considerable amount of recharge comes from the large boundary blocks.

The plots also show that the effect of injection on steam production is variable. For Case A with small recharge blocks (see Figure 9) injection enhances steam flow until about 45 years. However for Case B the zero injection case produces the largest steam flow after about 30 years and the pattern before then is confused.

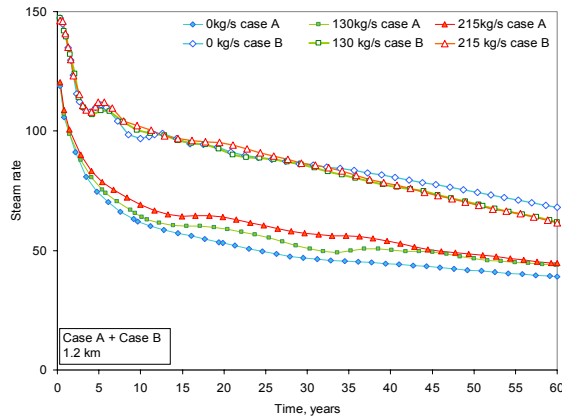


Figure 9. Steam production rates for a model with small side recharge blocks and very low permeability basement rock ($0.25 \times 10^{-16} \text{ m}^2$)

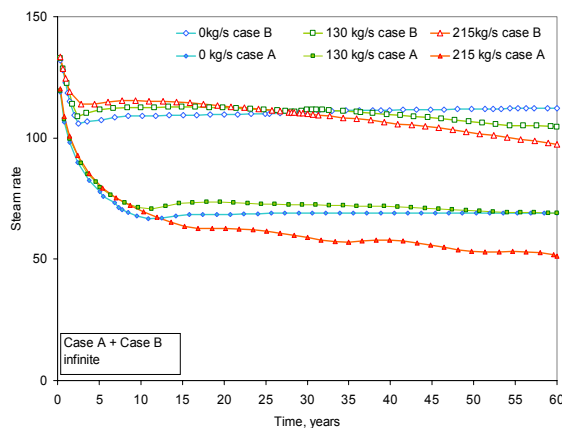


Figure 10. Steam production rates for a model with very large side recharge blocks and very low permeability basement rock ($0.25 \times 10^{-16} \text{ m}^2$)

For the model with very large recharge blocks (Figure 10) the long-term effect of injection is to reduce steam flow.

The significance of these results is limited because the initial temperatures and pressures in the boundary recharge blocks are the same as in neighbouring reservoir blocks. Thus all lateral recharge is hot water. In further studies a larger more realistic model will be used allowing for warm and cold temperatures in the zone surrounding the hot reservoir. This will enable the model to reproduce the observed effects of cold lateral recharge.

5. CONCLUSIONS

i) For the closed system investigated by Sigurdsson et al., 1995, injection increases steam

flow, but if the system is “opened” by allowing recharge from the top, the sides or the base, then the effect of injection is different.

ii) When the basement rock is sufficiently permeable a pressure decline in the reservoir causes deep recharge which in turn results in an increase in steam flow. However injection suppresses deep recharge and thus decreases steam flow.

iii) Lateral recharge may have a strong effect on reservoir behaviour. Both recharge from boundary blocks or injection can support the reservoir pressure, but recharge may be at a higher temperature than injection, thus better maintaining long term steam production.

This study shows that the effects of injection in a two-phase liquid dominated geothermal reservoir depend on the recharge conditions. Injection may increase steam flow if recharge is very small and the reservoir is acting as a closed system, but otherwise injection will decrease steam flow from production wells by suppressing hot recharge from depth or replacing lateral recharge by colder injected water.

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